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Sources of Variability and Inaccuracies in Aircraft Gas Turbine Emission Measurements

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Sources of Variability and Inaccuracies in Aircraft Gas Turbine Emission Measurements

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Emission Control Technology Division
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Gary F. Austin

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Abstract

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This report details and provides analysis of the various factors contributing to emission measurement inaccuracy. Discussion is presented for all major sections and components of the emission sampling system.

Prepared by

Approved
Project Manager - Aircraft

Approved
Branch Chief, SDSB

Approved
Division Director, ECTD

Distribution:

D. Alexander
J. DeKany
C. Gray
W. Houtman
G. Austin
R. Stork
H. Williams
G. Kittredge

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1.0 Introduction

This report presents an analysis of the sources of inaccuracies and variability propagated in the determination of the constituent levels of HC, CO, CO_2, NOx (NO + NO_2), and smoke in aircraft gas turbine engines.

The regulations promulgated by the Environmental Protection Agency for the "Control of Air Pollution From Aircraft and Aircraft Engines" (40 CFR Part 87) provide a well accepted procedure for determination of emission levels. These procedures provide the basis for analysis of the pollutant levels and are therefore the focal point of this report.

2.0 Summary and Recommendations

A. The sample transfer system for gaseous emissions has been shown to provide an adequate means of transporting the sample from the collection probe to the analytical equipment.

B. The analytical system provides analysis of the gaseous constituents consistent with the present state of the art.

C. Further consideration should be given to allow the use of a dryer in the CO and CO_2 (NDIR) system but only if valid correction factor for correction to a wet basis can be provided.

D. The sample probe extracts a representative sample of HC, CO, CO_2, and NOx for all non-afterburning engines except the mixed flow turbofan engines. Further study is required for the determination of probe design which provides a representative sample for the mixed flow turbofan engine.

E. Further study and a possible system modification is recommended for the smoke measurement system. Data indicates that it is difficult to obtain a representative sample by extraction of a sample from the gaseous emission probe.

F. To satisfy the calibration gas requirements of the regulations, there is a need for additional standard reference materials such as NO in nitrogen, intermediate levels of CO_2 in air, and higher concentrations of CO in nitrogen, and propane in air.

G. Ambient condition effects are the largest single source of a variability in gas turbine emission measurements. The EPA's Ambient Effect Program is addressing this problem.

H. Error analysis indicates that sample error is secondary only to ambient conditions in its contribution to the total exhaust gas measurement uncertainty.

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3.0 Sample Transfer System /Analysis (Gaseous)

The sample line must transport the extracted gas sample from the collection probe to the interface of the analytical instrument without affecting the concentration level of the constituents analyzed. EPA promulgated regulations (40 CFR Part 87) require that the sample line must be:

A. Constructed of either stainless steel or Teflon

B. Heated to 150 ^{0}C ± 5 ^{0}C (302 ^{0}F ± 9 ^{0}F) prior to the flame ionization detector

C. Heated to 55 ^{0}C ± 5 ^{0}C (131 ^{0}F ± 9 ^{0}F) after the flame ionization detector

D. In no case shall it be longer than 24.4 meters (80 feet)

E. Capable of transporting the sample from the probe inlet to the analytical equipment in 2 seconds or less.

F. Of 0.46 to 0.81 centimeters (0.18 to 0.32 inches) inside diameter.

3.1 Sample Line Temperature

Maintenance of the sample line temperature at the prescribed temperature levels is mandated due to concern for water vapor and hydrocarbon condensation in the line. Gas turbine engines operated with up to 8% water vapor in the exhaust of which about 4% can be attributed to the combustion reaction of the hydrocarbon fuel. The remainder of the water vapor is contributed by the background concentration of humidity. A sample line temperature of 50 ^{0}C will prevent water vapor condensation in the sample for all practical operating conditions.

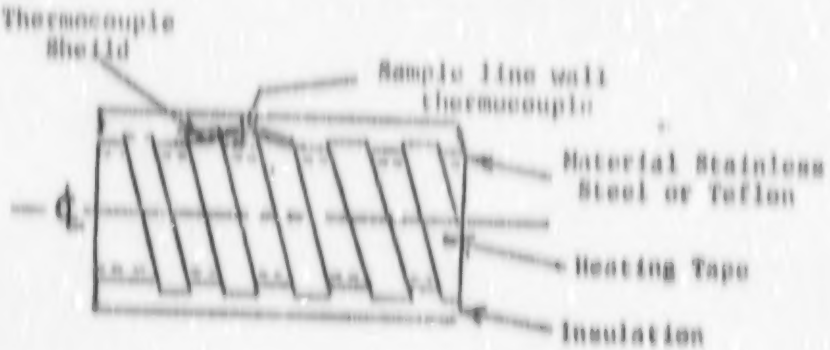
Although only a limited amount of data [1] [2] is available on the analysis of the condensable hydrocarbon compounds present in the exhaust of gas turbine engines it supports the need to maintain the sample [illegible] or greater prior to hydrocarbon analysis. Boiling point data of the hydrocarbon compounds identified in [illegible] that this temperature will insure that compounds which have a carbon number of 13 or less will remain in the vapor state. The partial pressure effect on the hydrocarbon compounds present in the system which operates at subatmospheric pressure further insures against condensation because of the reduced boiling point of the mixture.

Data [2] on concentration levels of the identified hydrocarbon compounds is presented in Figure 1 (Appendix). It was collected by cryogenically trapping the hydrocarbon compounds. A second study [1] was conducted by cryogenically trapping the higher boiling point compounds and bag sampling the remainder of the noncondensable compounds. Results of both of these studies indicated that for Jet-A fuel, 95% of the

hydrocarbon compounds present in the exhaust have a carbon number of 11 or less. For other fuels such as DF-2 and JP-4 this percentage was lower and there would therefore be greater concern for condensation of hydrocarbon compounds at a sample temperature of 150 °C. The maximum temperature which the sample can be heated to is limited only by practical and mechanical limits of the system.

A high temperature (150 °C) is further supported by the length of time required for the system to purge itself of possible contamination encountered during start up or transient operation of the engine. Experience has shown that a low temperature contaminated system may require up to 30 minutes to stabilize to background levels. This length of time is greatly reduced in higher temperature systems.

The procedure used for the determination of the sample (sample line) temperature is also of extreme importance. It is desirable but impractical to measure the actual sample temperature in the sample line. It is also important that the sample line surface be maintained at the prescribed temperature and be free of any cold spots where condensation would be encouraged. It is therefore practical to determine the temperature of the sample line (see sketch) in a sufficient number of locations along the line length to ensure against any cold spots. Presently this is not clearly specified in the EPA regulations.



Sample Line Construction

3.2 Sample Line Material

The use of stainless steel or Teflon as the non-reactive sample line material to be used for transport of the gaseous sample has previously been established[3,4,5]. No evidence has been presented which establishes concern for these materials inability to maintain the integrity of the sample during transport to the analysis instruments.

3.3 Sample Line Flow Rate

The difficulty of transferring the sample from the sample line inlet to the analysis instruments in the required two seconds or less is compounded by the requirement that 30 liters per minute of the sample be bled off in the instrument system. Since the maximum flow rate is a function of the pressure drop in the sample line, systems which require the maximum line length of 24.4 meters will necessitate the use of a high capacity vacuum pump. A study [5] of the capabilities of various system designs including variations in the sample line length substantiated that these requirements could be met.

The need for the short transfer times [5] is established through concern that a molecule of exhaust gas should have a minimum residence time at any point in the sample line to discourage condensation of any constituent and deter possible chemical reactions.

Concern primarily from industry that these requirements are severely restrictive and are unnecessary to insure the integrity of the sample has not been documented with substantiating evidence. It is therefore felt that the sample line flow requirement can be maintained at their present level.

3.4 Sample Line Length

It has been established [3][5] that the sample line length should not exceed a length of 24.4 meters (80 feet), otherwise sample integrity may be compromised. A study [3] conducted for the EPA by Scott Environmental Technology demonstrated that for sample lines up to 80 feet in length the sample integrity is maintained (Table 1). Lengths longer than 80 feet were not tested in this study. The need to allow sample line lengths in excess of 24.4 meters is therefore not warranted except for possible isolated incidences where lengths 24.4 meters or less are physically impossible. In this case the burden of insuring the sample integrity should be placed on the agent seeking the variance from the regulations.

Table 1.

Emission Measurements Made through a Heated Stainless Steel Sample at 150° and a bypass flow of 30 L/M

Sample Line Length (ft)	THC[a] PPM-C	CO PPM	CO_2 %	NO_x PPM
80	167	337	1.48	11.7
80	168	329	1.48	11.9
40	173	337	1.48	11.9
40	168	329	1.48	12.1

[a] The Hydrocarbon Sample Line used was 20 feet shorter than that indicated.

4.0 Analytical Sample System Analysis (Gaseous)

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4.1 Hydrocarbon Analyser

The Flame Ionization Detector (FID) is specified as the instrument to be used for the determination of the total hydrocarbons present in the exhaust. This instrument operates on the principle that a pure hydrogen-air flame produces very little ionization. When a hydrocarbon compound is introduced into the diffusion flame a chemical ionization is produced. This ionization potential is proportional to the number of carbon atoms present in the hydrocarbon molecules. The instrument's ability to respond in an approximately linear manner to saturated, unsaturated and aromatic carbon atoms in a variety of organic structures provides a realistic method of monitoring the total mass emission of hydrocarbon compounds.

The reaction chamber and all sections of the analyser exposed to the sample are heated to approximately 160 °C (320 °F). This relative high temperature is required to assure that minimal condensation of gaseous hydrocarbon compounds in the sample system occurs. As previously stated, existing data [illegible] on the hydrocarbon compounds present in the exhaust of gas turbine engines indicates that approximately 95% of the hydrocarbon compounds present have a carbon number of 13 or less (Figure 1). This evidence coupled with the effect of the partial pressure on the mixture will deter any possibility of hydrocarbon condensation.

The two predominate sources of inaccuracies in this analysis system are synergism (oxygen interference) and its response (linearity) per unit carbon atom to all hydrocarbon compounds. It is difficult to predict quantitatively the effective interference level contribution from oxygen in the sample. Excess oxygen in the sample changes the nature of the flame from a pure diffusion flame to a premixed one with a higher flame temperature. This higher flame temperature enhances thermal cracking and rapid oxidation of the hydrocarbon compounds. As previously stated, the EPA regulations provide a check of the detector response for the oxygen effect by introducing various concentrations of oxygen into the sample and determining their effect on measured levels. Maximum limits of interference are placed on this effect. The instrument's linear response to hydrocarbon compounds (differential hydrocarbon effects) is checked and the detector response optimized by introducing a mixture of propane in air to the burner and adjusting the burner fuel and background air flow to optimum response.

4.2 Carbon Monoxide, Carbon Dioxide Analysers

The nondispersive infrared (NDIR) analyser is specified for the determination of concentrations of both carbon monoxide (CO) and carbon dioxide (CO_2). In this instrument the gas being measured is used to detect itself by comparison to a reference gas. The method of detection is based on the principle of selective absorption. The infrared energy

of the particular wave length of the gas being measured will be absorbed by that gas and the infrared energy of other wave lengths will be transmitted. The detector determines this absorption by difference and records it.

Interference in the NDIR measurements may arise if the exhaust sample contains other species which will absorb radiation at the same frequencies as the gas being measured. For example the water vapor and CO_2 absorption spectra will interfer with that of CO. The use of a dryer to eliminate the water vapor interference problem would provide a means of avoiding part of the problem. This creates an additional problem in that a correction factor for the conversion of the mass pollutant level of the constituent from a dry basis to a wet basis would have to be provided. At the present time a definitive correction factor for this conversion has not been documented. Since it is the intent of the regulations to determine the levels of CO and CO_2 on a wet basis a procedure is provided to determine and correct this interference. The procedure provides for the passing of a known range of carbon dioxide and water vapor through the CO instrument and observing the response. If the effect is greater than two percent of the measured carbon monoxide level all subsequent measurements must be corrected for this interference. Further consideration should be given to allow the use of a dryer in the CO and CO_2 (NDIR) system but only if valid correction factor for correction to a wet basis can be provided.

One additional problem which can create discrepancies in the determination of CO and CO_2 levels is the presence of condensed water vapor in the system. A blockage in the system which would affect the instrument working pressure will effect the instrument calibration (A5" H_2O= 1% change in the instrument calibration). Extreme care must therefore be taken to prevent water vapor condensation.

4.3 Oxides of Nitrogen Analyzer

Chemiluminescent analysis is the method of analysis required for measuring the emission levels of NO and NOx. This analysis technique utilizes the principle that nitric oxide (NO) reacts with ozone (O_3) to yield nitrogen dioxide (NO_2) and oxygen (O_2). Approximately 10% of the NO_2 is electronically excited. The transmission of the excited NO_2 to the ground state yields light emission. The intensity of the light emission is proportional to the mass flow rate of NO in the reactor. To determine the level of NO_2 in the exhaust and therefore the total NOx (NO + NO_2) in the sample, conversion of NO_2 to NO is provided by a thermal converter. An efficiency check of the converter is provided to ensure that at least 90% of the NO_2 is converted to NO.

Condensation of water vapor or hydrocarbon compounds in the chemiluminescent instrument system is also a persistent danger to the integrity of the sample. The two predominate effects are the solubility of NO and NO_2 in the condensed hydrocarbon compound (small effect) or water

vapor, and a water droplet blockage in the system which would effect the sample flow-rate. One approach to the solution of this problem would be to remove the objectional constituents in a manner which maintains the integrity of the NOx sample. This could be accomplished by using a dryer similar to that described for the alternative NDIR procedure. A second approach and that required by the EPA Regulations is to heat the sample to a temperature which is above the dew point for the water vapor at the system operating pressure. This will prevent the loss of NO and NO_2 due to their solubility in water and limit any loss due to hydrocarbon absorption.

5.0 Sample Probe Analysis (Discussion)

The sample probe as required by the EPA regulations shall have a minimum of 12 sampling points either mixed into an integrated sample or individually sampled with separate analysis for each. If a mixing probe is used the orifices shall be of equal area. In all cases the probe shall be designed such that 80% of the total pressure drop of the probe assembly will be taken at the probe orifice or orifices and it shall provide a representative sample.

The sample probe is therefore required to collect a representative sample without bias to any constituent (HC, CO, CO_2, NOx and Smoke), and to transport the sample to the sample line unreacted or modified in any manner. In non-afterburning engines this mechanism is simplified by the fact that the exhaust gas reaction of the constituents of concern is complete at the sampling point. The complexity of extracting a representative sample from the exhaust plume of a mixed flow fan engine can be illustrated from studies [3][4] conducted which detail the exhaust gas pollutant levels on concentration isopleths, (Figure 2, 3, 4). This data was collected from a detailed traverse of the engine exhaust. These figures show the non-uniform characteristics of these constituents and the difficulty experienced in attempting to design an integrating probe which would provide a representative sample for all constituents. Also, this situation is further complicated by changes in concentration profiles with power setting. The exhaust gas profiles for turbojets and non-mixed flow turbofan engines are not nearly as complex and are uniform when compared to the mixed flow turbofan engines. Probe design for mixed flow engines is more difficult than for the nonmixed flow engines, in fact, attempts at probe design for mixed flow engines such as the JT8D and Spey have been unsuccessful, and show discrepancy of about 25% when compared on a carbon balance basis.

A comprehensive study was conducted by the EPA[4] to determine if mass flow weighting of the constituent concentration instead of the area weighting technique presently required would provide a means of extracting a representative sample for mixed flow engines. Results of this study did not provide a satisfactory method of extracting a representative sample on a mass flow basis.

A second test for sample representativeness is the comparison of the total number of carbon atoms in the extracted sample to the total number calculated from the fuel and air flow (carbon balance). This is commonly done by comparing the calculated vs the measured fuel to air ratio (F/A). The F/A ratio for exhaust gas emissions is given in the simplified formula:

$$F/A\ Exhaust = \frac{.807 - .2\left(\frac{CO}{10^4}\right) - CO_2}{\frac{HC}{10^4} + CO_2 + \frac{CO}{10^4}}$$

The emission concentrations of typical present day class T2 are:

	HC	CO	CO_2
Idle	400	450	1.6
Take off	3	10	3.5

where:

CO and HC are in PPM
CO_2 is in %

As can be seen by the above equation the representativeness of CO and HC is not really tested because the relative value of the CO_2 concentration is predominate over the HC and CO concentrations. NOx and Smoke are not tested in this method for representativeness.

At present the two techniques described above provide the best method of demonstrating the representativeness of the sample extracted.

Manufacturers of mixed flow turbofan engines (Pratt and Whitney Aircraft and Rolls Royce) are conducting in-house investigations with the intent of developing an acceptable probe. It is therefore recommended that these programs be monitored closely to determine if progress is being made towards the design of a representative sampling technique for mixed flow turbofan engines. If a solution can not be found there are two alternatives to consider.

A. Continue to require that they comply with the probe design requirements of the EPA Regulations (40 CFR Part 87).

B. Require a detailed traverse of the exhaust plume to provide an acceptable representative sample.

6.0 Smoke Sample Collection and Analysis

This section presented separately from the gaseous system analysis because of unique problems which exist with this procedure.

The smoke sample system as specified in the EPA regulation requires that the smoke sample be extracted from the probe or sample line used in the gaseous emission analysis system. The sample is then transported through a stainless steel or copper, heated, (above the dew point) line with a maximum length of 22.9 meters (75 Feet) to the sample collection system. The sample collection system consists of a filter holder and sample measuring devices. The filter holder collects a series of 4 stained spot filter samples. From these filter samples the actual smoke number is determined and reported for each power setting using a reflectometer.

6.1 Smoke Sample Collection and Analysis

The procedures and mechanisms used in the collection of the stained filter sample are generally considered to be acceptable and provide a representative analysis of the sample presented to it. The only exception to this is the requirement that 4 stained filter samples shall be collected at each power setting. Collection of these 4 one minute samples plus the time required for the system to stabilize requires approximately 5 minutes of engine running time at each power setting. This procedure becomes particularly burdensome at the take off power setting where the required time is often in excess of the manufacturers recommended operating procedure.

The four filter samples are required because the determination of the smoke number is based on a linear least squares fit line of the reflection density smoke number vs the sample weight per square inch of filter spot area. Fewer than four filter samples would therefore effect the accuracy of the smoke number calculated because of its adverse effect on the least squares line accuracy.

Even though there would be an adverse effect on the calculated smoke number accuracy, consideration should be given to the reduction in the number of filter samples required at the take off power setting. A reduction such as this would have an added advantage of conserving fuel.

6.2 Smoke Transfer System

As described above the smoke sample is to be extracted from the gaseous emission sample line (or probe) and transported to the smoke sample collection system. Review of the evidence presented in section 5 indicated that in some cases it is quite difficult to supply a representative gaseous emission sample. Investigations [6] have shown that for a mixed flow turbofan engine the 12 point integrating, manifolded probe

will not yield a representative smoke sample. In this study, the investigator relied on a multipoint rectilinear traverse of the exhaust plume to provide a representative sample for certification of the engine.

There are several factors contributing to the non-representativeness of the smoke sample.

A. Investigation has shown [11], that the sample line connection (Tee) where the smoke sample is extracted from the gaseous emissions sample can have an adverse effect on the smoke level (lowering the level by as much as 4 smoke numbers when gaseous and smoke samples are measured simultaneously).

B. If the two emission levels are determined independently with a 12 point sample probe, the requirement that 80% of the pressure drop in the probe assembly must be taken at the probe orifices, requires the probe orifice diameters to be so small that problems are experienced [11] with orifice blockage from carbon particulates.

C. A sample probe designed to provide a representative sample from the carbon balance technique will not ensure representativeness of the smoke sample.

Confusion is added to the smoke sampling technique by the schematic drawing of the smoke sampling system presented in the regulations, 40 CFR Part 87, Figure 5. It shows a separate and unique sampling probe and is not interconnected to the gaseous system as shown in the gaseous emissions system schematic, Figure 3.

To reduce the inherent inaccuracies of this system and to provide assurance of a representative smoke sample, revisions to the smoke measurement procedure should be considered. A system such as that recommended by the SAE in ARP 1179, which requires a multipoint traverse, would provide a data base. From this data a unique single point or intergrating smoke probe of less than 12 points could be designed and representativeness shown prior to smoke certification testing. This system would not rely upon the gaseous sampling system and avoid its inherent disadvantages for smoke sampling.

7.0 Effect of Variations in Ambient Conditions

Variations in ambient conditions (temperature humidity and pressure) have been shown to effect the pollutant constituent levels HC, CO, CO_2, and NOx of gas turbine engines. Concern for this problem developed several years ago when Marchionna [7] and Lipfert [8] identified correlations of emission (NOx) changes to combustor inlet temperature and humidity. The EPA addressed this problem in the regulations by stating "Projects are being started to define these relationships so as to allow introduction of suitable correction factors as soon as possible."

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The program undertaken by the EPA to define these relationships for HC, CO, NOx, and Smoke is a three task effort. The first task which is nearing completion is the full scale engine testing under controlled temperature, humidity, and pressure conditions. The second task which presently is being contracted is combustor rig testing of engine combustors under controlled conditions. The third task is the analysis of generated and existing data to provide determination and formulation of these effects. Results of this program are expected in January of 1977.

Results to date have not indicated whether one set of correction factors will uniformly apply to all classes and types of engines or whether a different and unique set will have to be developed for each.

7.1 Ambient Conditions Effect on NOx

Of the various parameters affecting NOx concentrations, combustor inlet air temperature has been found to cause the largest variation. The effect of humidity is the second largest with both temperature and humidity effects following the exponential form:

$$EI_{NOx}\ (\text{corrected}) = EI_{NOx}(\text{indicated})\ e^{c\ (\text{Temp. or Humidity})}$$

The effect of pressure on NOx concentrations is relatively mild compared to the temperature effect and follows the kinetic reaction prediction of approximately the square root of the pressure:

$$EI_{NOx}(\text{corrected}) = EI_{NOx}(\text{indicated}) \left(\frac{P_{\text{reference}}}{P_{\text{indicated}}}\right)^{1/2}$$

Considerable information has been generated for the effects of ambient conditions on NOx by government and private agencies. Although this work has been done under uncontrolled conditions it does verify the forms of the equations given above. The remaining factors to determine are the constants to be used in the equations and whether a single equation will apply to all engine types.

7.2 Ambient Condition Effect on HC, CO, and Smoke

The EPA's ambient effects program (described above) is essentially the first formal effort conducted toward the understanding of the effects of ambient conditions on HC, CO and Smoke. The effects on HC and CO do not lend themselves to theoretical chemical kinetic analysis as is the case for NOx because of the complexity of the reactions. Also since HC and CO are predominate at low power (idle) where the combustion efficiency is low and engine variability is high it has been very difficult to analyze and statistically treat the existing data to determine the effects. The effects of ambient conditions on smoke is unknown but is expected to be small.

7.3 Magnitude of Variability

The magnitude of the effect of changes in ambient conditions on exhaust gas constituent emission levels is the largest single sources of variability in gas turbine engines. In a study [157] conducted for the EPA under controlled ambient test conditions it was shown that with increasing temperature there were decreases in hydrocarbons, and carbon monoxide and increases in the oxides of nitrogen. With increasing humidity there were increases in hydrocarbons and carbon monoxide and a decrease in the oxides of nitrogen.

8.0 Background Concentration Effects

background concentration levels (ambient air quality) of the gaseous constituents being measured are of concern and do contribute to the total engine emission level measured. The process of certifying an engine to a specific emission level should rightly consider these effects but at the present time a procedure has not been determined. The total contribution to the emission EPAP level from the background concentrations is shown below. The background levels used in these calculations were derived from typical levels experienced during testing at various manufacturers. The background levels are:

Hydrocarbon	=	3 ppM
Carbon monoxide	=	.06 vol %
Oxides of nitrogen	=	.5 ppM

Background Effects on EPAP

	HC EPAP			CO EPAP			NOx EPAP		
Engine	As read	Corrected	Δ%	As read	Corrected	Δ%	As read	Corrected	Δ%
JT8D-11[155]	0.61	0.73	+19.67	16.10	16.65	+3.42	0.89	0.90	+0.94
JT8D-11[156]	0.66	0.81	+24.24	15.50	16.12	+4.00	1.25	1.29	+3.61
TFE 731[158]	0.069	0.16	+56.70	16.48	16.86	+2.35	10.07	10.12	+ .5

In the cases presented above the background levels were assumed to pass through the combustor unreacted and thus contribute directly to the total Exhaust Emission level.

Determination of the background level contribution for HC and CO to the total emission level is difficult to access because these constituents are partially consumed or reacted during the combustion process in the engine. The determination of this effect would be further complicated in a mixed flow turbofan engine where only a portion of the background constituents would pass through the core of the engine.

To study this effect in greater detail and to provide a correction technique for each engine type, a complex program of uniformally introducing a known concentration of pollutant at the engine inlet and comparing

the resultant exhaust gas pollutant level to that of a different (preferably zero) background level, would have to be run.

At the present time, it is expected that background constituent levels would have an effect on the total pollutant levels. The certifying agent should be cautioned as to their possible influence. This effect would be particularly influential where the possibility of recirculation or contamination from other test cells exist.

9.0 Calibration Gas Accuracy

The EPA regulations require that instrument calibration gases used for emission measurements have an accuracy of ± 2% of the true value. These working gases are third level gases with NBS primary standards (± 1% accuracy) as first level and laboratory reference gases as the second level. There are several problems related to calibration gases which effect accuracy:

A. A number of standard reference gases have been developed by the National Bureau of Standards (NBS) for use in the automotive industry, some of which are also suitable for gas turbine exhaust measurements. To satisfy the requirements of the regulations, there is a need for additional standard reference materials such as NO in nitrogen, intermediate levels of CO_2 in air, higher concentrations of CO in nitrogen, and propane in air.

B. Difficulty is experienced in maintaining certain reference gases with confidence of assay, particularly due to instability in the cylinder. This particularly becomes a serious problem when attempting to purchase gases of the high purity and accuracy of assay.

C. The regulations presently specify an accuracy figure without stating a required confidence interval. To properly specify the accuracy of a gas a confidence interval should be stated.

10.0 Variability and Repeatability of Engine Parameters

Variation in engine operation such as approach to power and run to run changes coupled with inaccuracies in the critical instrumentation parameter (thrust, or horsepower) do effect the EPA thrust based emission level parameter (EPAP). Other instrumentation errors effect the calculations for representativeness by the carbon balance technique. These are engine air flow and fuel flow. In general these instrumentation errors include both precision and bias inaccuracies.

The thrust measurement accuracy in terms of a 50,000 pound measurement system might reach 500 pounds (1% of full scale). The rate of change of NO_x emissions with thrust and the uncertainties in the NO_x

measurement itself show that 500 lbs. thrust uncertainty is a negligible contributor to EPAP NOx uncertainty. The case of CO and HC, however, is quite different. In the idle region, the only region contributing significantly to CO and HC, EPAP, 500 lbs. uncertainty in thrust setting will result in a 12% error in carbon monoxide in EPAP and 35% error in Total Hydro-carbon EPAP. Running several points in the region of idle and picking off the true idle thrust point from a curve fit would reduce much of the uncertainty contributing to the EPAP uncertainty.

Analysis of the engine air flow and fuel flow indicate that the uncertainties at high power are usually on the order of 1- 2 as this is the design point of the engine. In the region of idle, however, air flow is usually not clearly delineated in the engine testing as it is in "off-design" operation. The air flow measurement uncertainties of less than 0.5% may result in 5-10% air flow uncertainties. Fuel flow uncertainty remains relatively constant throughout the engine operating range and is insignificant when compared to air flow uncertainty particularly at idle power.

The effect of approach to power and run to run variability, can be illustrated from a study conducted for the EPA by Scott Research Labs[19]. The approach to power did not have a significant effect on the CO and NOx emission indicies but did show THC emission indicies to have a heavy dependence on the approach to power (Figures 5, 6, 7). Run to run variation showed that the greatest uncertainty also to be in the THC emission indicies, where the coefficient of variation was 5.3%. The coefficients of variation for CO and NOx were 1.5% and 3.5%, respectively.

11.0 System Accuracy

Assessing gas turbine emission levels requires a knowledge of the measurement accuracy. The assessment of emission measurement uncertainty requires properly combining the uncertainties in both emission measurement and related gas turbine performance parameters to obtain a total uncertainty.

Emission measurement uncertainty results from calibration gas analysis uncertainty, instrument precision, sample error, the effects of ambient factors such as temperature, humidity and pressure and background pollutant levels. These are illustrated in figure 8. Also contributing to the total uncertainty is the particular constituent being analyzed and the absolute magnitude of that constituent. The related gas turbine parameters whose uncertainties have previously been considered include thrust and fuel-air ratio.

At the present time a comprehensive understanding of the individual uncertainty and its contribution to the total measurement uncertainty is poorly understood. This is partially because the emission measurement

system, which represents an advanced state of the art in technology, is a combination of subsystems, associated mechanisms and components which react and interact to form a composite system of high complexity. Further detailed analysis of the system and its components contribution to the total uncertainty is needed to provide a comparative assessment of variability within the system and from system to system. Knowledge of within the system uncertainty and its contribution to the promulgated EPAP level would provide the certifying agent a better understanding of the systems ability to analyse a given constituent and whether the system is supplying a representative exhaust gas sample for analysis. An understanding of system to system uncertainty is important because a standardized comparative base must be established for verification of the certifying agent's calculated EPAP level. It is therefore recommended that consideration be given to conducting a comprehensive study into the component and system accuracy and its influence on the constituent EPAP level.

The following is an assessment of the basic sources of variability, their approximate range of inaccuracy, and their approximate contribution to the systems total EPAP inaccuracy. It must be remembered that this is only an approximate range of inaccuracy and that dependent upon analysis of the individual systems these levels may vary greatly.

Contribution to Inaccuracy

	Range of Inaccuracy - %	Contribution to Total Inaccuracy-%
Sample Error		9
Sample line and Probe	0 to 25	
External Influencing Factors		
Background Pollutant levels	0 to 5	
Effects of Changes in Ambient Conditions	0 to 50	
Engine Effects		5
Performance Parameters		
Thrust	0 to 25	
Fuel to Air Ratio	0 to 10	
Run to run	0 to 5	
Approach to Power	0 to 5	
Instrumentation Error		
Calibration Gases	1 to 6	1.7
Analytical Instruments	3 to 4	3
Expected System Inaccuracy		
(Not considering Ambient Conditions)	5 to 25	10.4

As can be seen from the data presented above engine inaccuracies and inaccuracies created in the analytical system are small when compared to the sample error. The sample error is largely due to the fact that a non-uniform concentration of exhaust is sampled at a discrete number of points.

Data presented by Dinsk[9], table II, illustrates typical levels of total precision error associated with the CO, HC, and NOx measurements for a single point sample for T2, T1, and T4 class engines. (T2 = high bypass fan engine; T1 = turbofan engine; T4 = mixed flow fan engine). Total precision error is a combination of sample error and instrument precision error given by the equation:

$$\text{Precision Error} = \{(\text{Sample error})^2 + (\text{Instrument precision error})^2\}^{1/2}$$

Table II. Total Precision Error, %

Engine Class	Low Power CO Precision	Low Power THC Precision	High Power NOx Precision
T2	± 32	± 79	± 22
T1	± 42	± 53	± 17
T4	± 61	± 59	± 64

The precision error is 2σ over the 95% confidence interval and it means, for CO for example, that 95% of the time, single point samples of CO at low power in the T2 class engine tailpipe will be within ± 32% of the mean.

The term usually involved in emission evaluation is the mean of several measurements. Variation in that mean is to be expected and may be estimated by a quantity called the precision of the mean. The precision of the mean may be defined as the precision of the data divided by the square root of the number of data points sampled:

$$\text{Prec. of mean} = \frac{\text{Prec. of data}}{(\text{No. of single point samples})^{1/2}}$$

For example, the precision of the mean for the T2 class engine CO data in Table I would vary by the square root of the number of single point samples as shown in Figure 9.

The dependence of the precision of the mean on the number of sampling points is clearly shown as is the relatively minor contribution of instrument precision to the overall precision of the mean. (Although both the precision of the mean, and the instrument precision contribution to the uncertainty decrease as the number of sampled data point increases, the uncertainty in the average will never be less than the uncertainty in the calibration gases, called calibration gas bias.) Except for the magnitude this comparison between instrument and sample error for CO is generally applicable for all constituents and all engine testing where data was taken from various points in the engine exhaust as previously shown by Nelson[10].

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APPENDIX

Figure 1

Organic Compounds in Turbine
Combustor Exhaust Using JP8 Fuel

This results was extracted from data collected and reported by Dr. James P. Conkle of the USAF School of Aerospace Medicine, Environmental Science Division, Brooks AFB, Texas.

Analysis of Hydrocarbon compounds present in the gas turbine exhaust of a T-56 combustor using JP8 fuel. JP8 fuel is very similar to commercial ASTM-D1655-Jet A.

Compound Family Identified	Total*	Carbon Numbers Up to 8	9 to 11	11 and up
Paraffins	.6207	.1489	.436	.0358
Olefins	1.0586	1.0136	.045	"
Diolefins	.046	.046	"	"
Naphthalenes	.104	.104	"	"
Aromatics	.635	.58	.055	"
Aldehydes	.331	.331	"	"
Alcohols	.118	.118	"	"
Ketones	.3258	.3137	.0121	"
Ethers	.0761	.0761	"	"
Esters	.0232	"	"	.0032
Nitrogen Containing	.0119	.0119	"	"
Peroxides	.0023	.0023	"	"
	3.3326	2.7455	.3141	.0190

% of Total HC

Carbon Numbers up to 8 = 82.4%
Carbon Numbers up to 12 = 98.8%
Carbon Numbers 13 and up = 1.17%

*PPM as Hexane

THC (ppm)

CO (ppm)

CO_2 (%)

NO_x (ppm)

FIGURE 8

NOZZLE TRAVERSE - P&W JT8D IDLE POWER

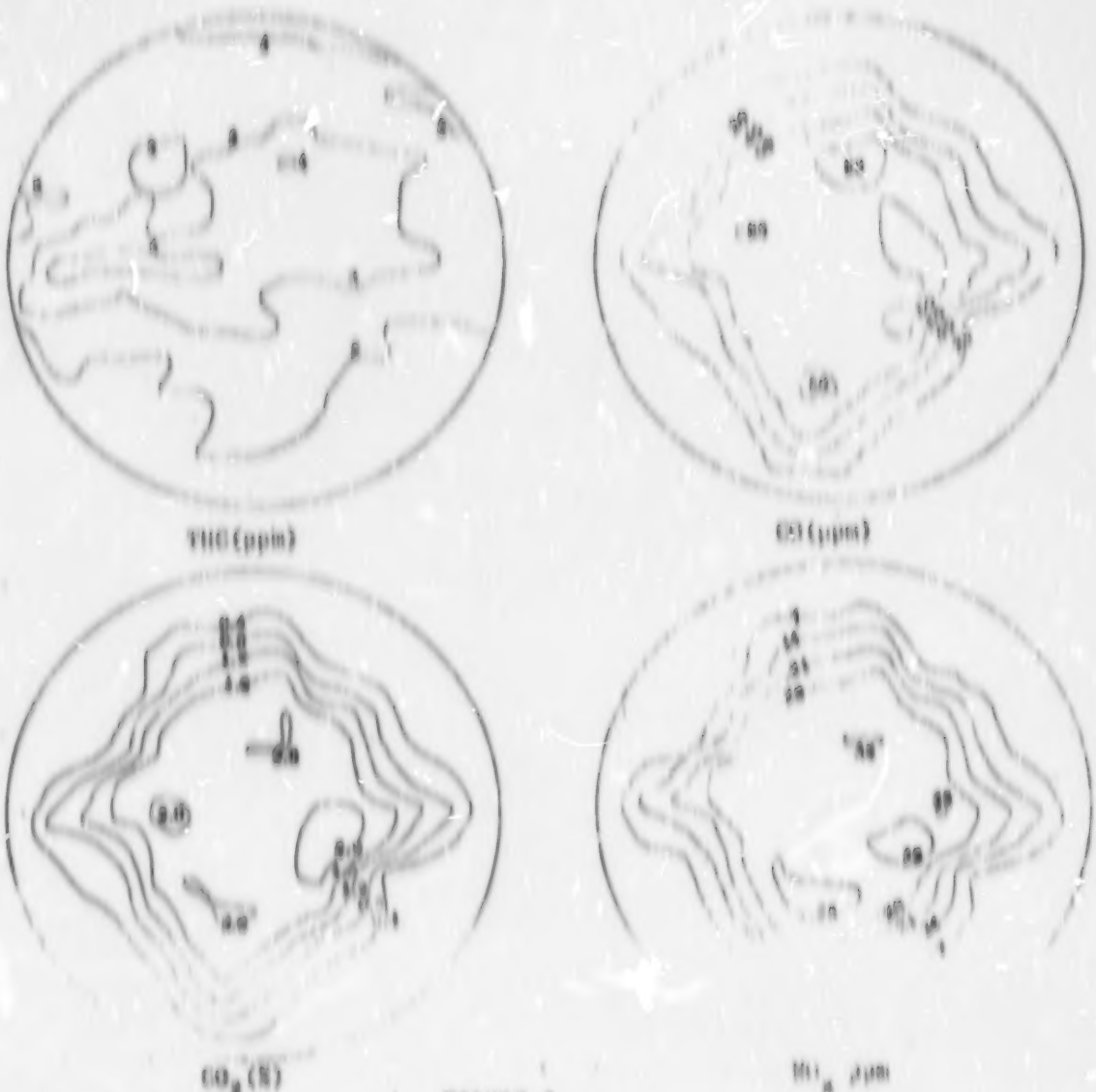

FIGURE 3
NOZZLE TRAVERSE - P&W JT8D APPROACH POWER

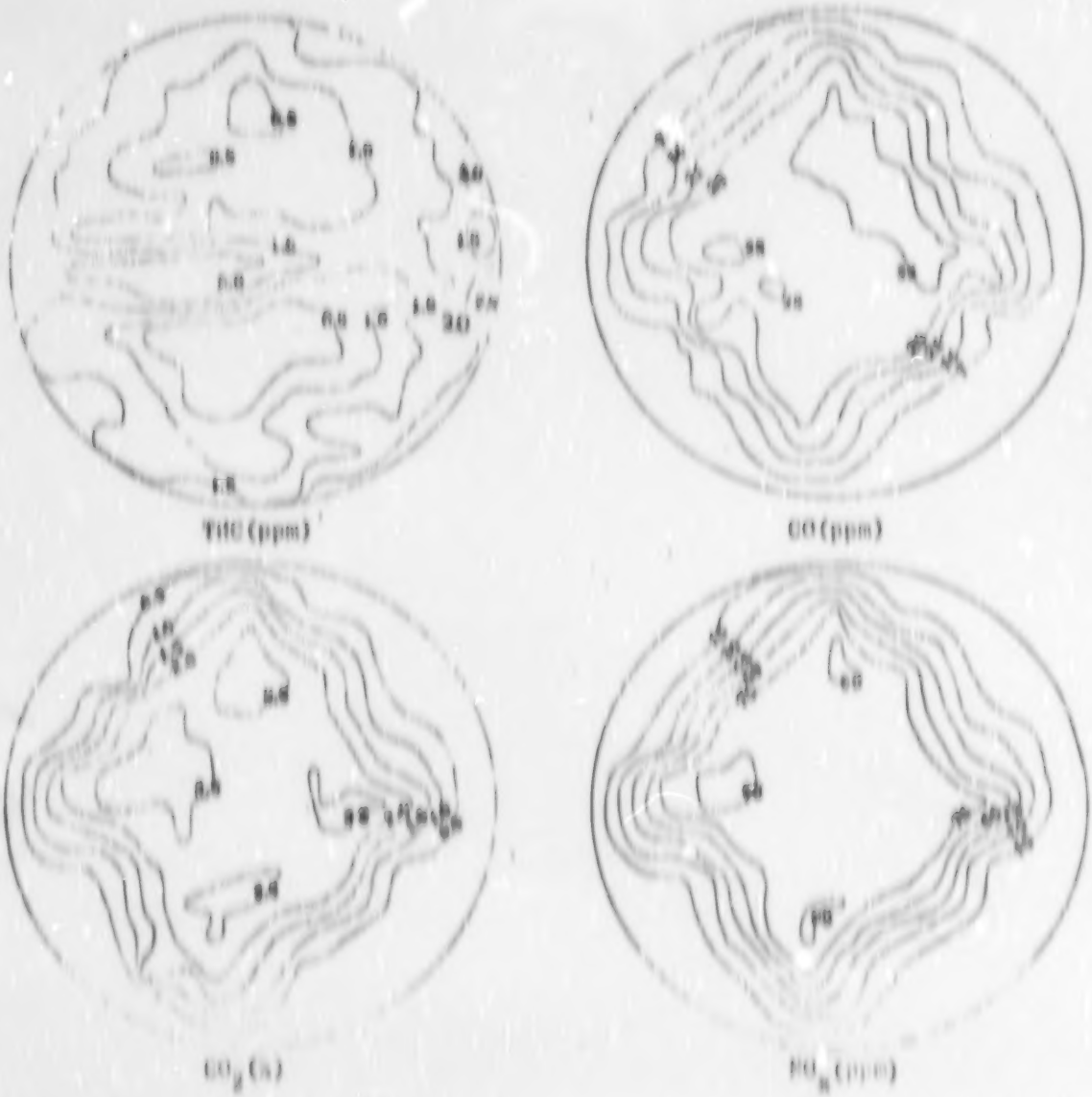

FIGURE 4

NOZZLE TRAVERSE - 36W JT8D MAXIMUM CONTINUOUS POWER

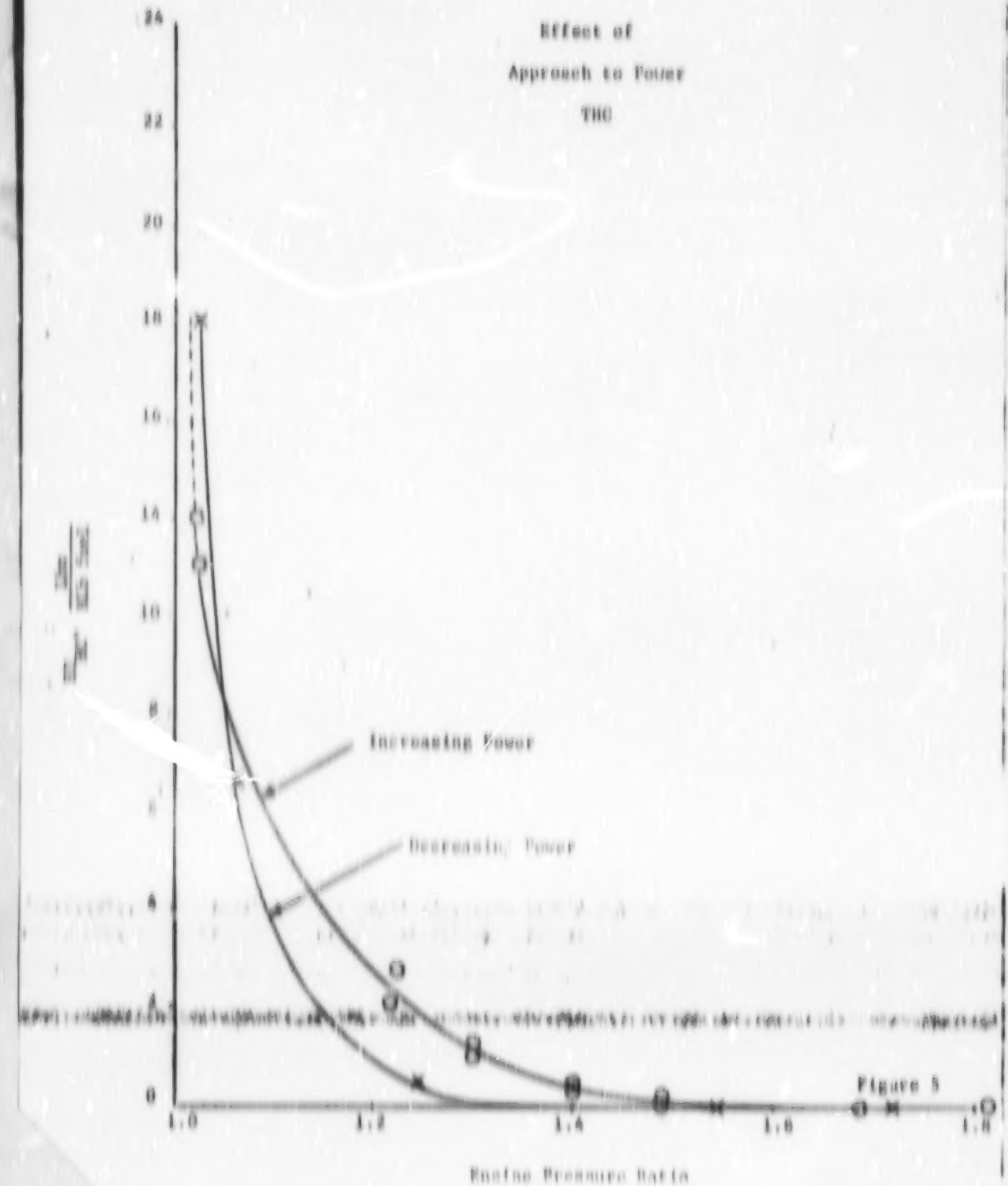
Effect of
Approach to Power
THC
24
22
20
18
16
14
12
10
8
6
4
2
0
Increasing Power
Decreasing Power
1.0
1.2
1.4
1.6
1.8
Engine Pressure Ratio

Figure 5

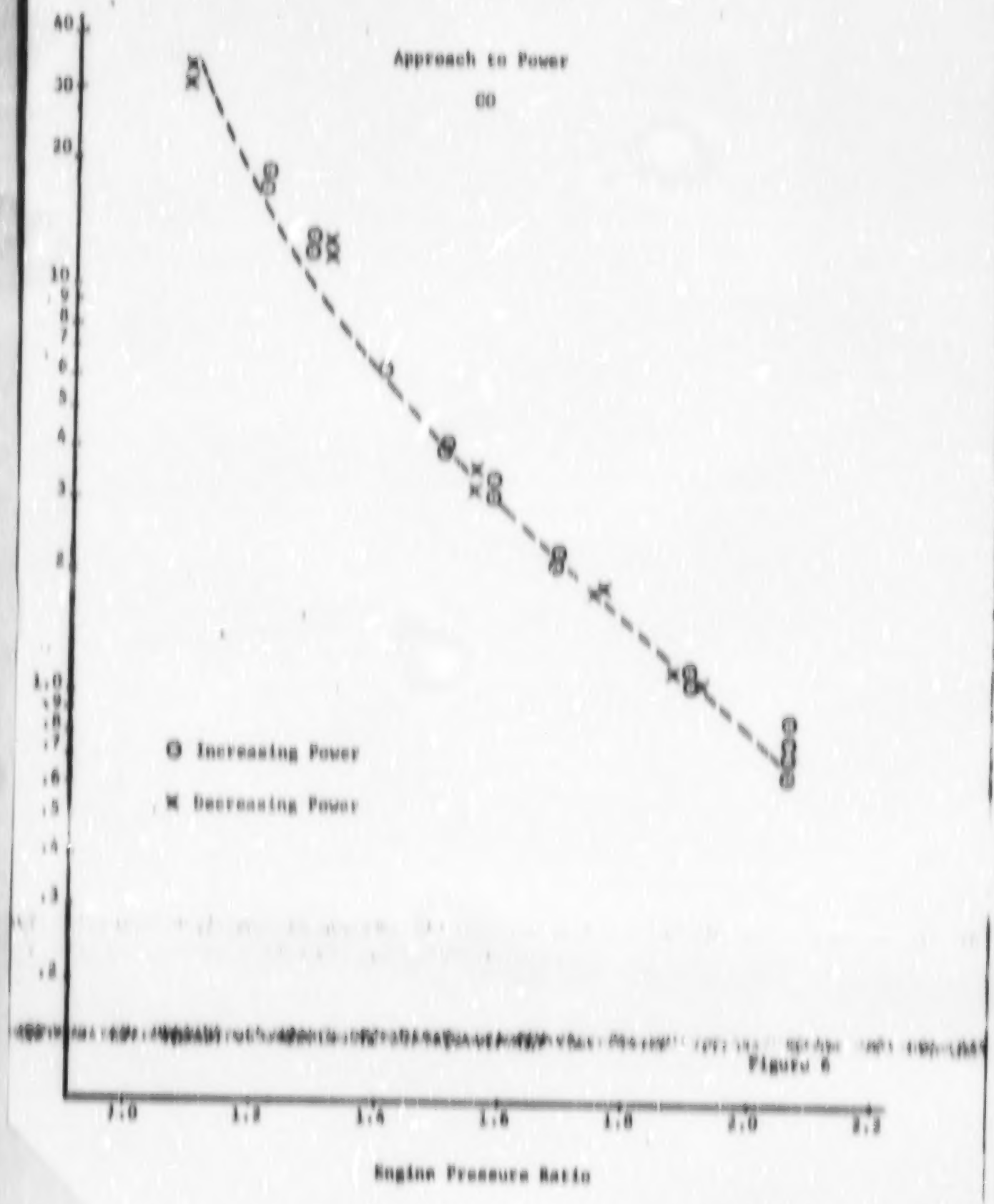
Approach to Power
Idle
40
30
20
10
9
8
7
6
5
4
3
2
1.0
.9
.8
.7
.6
.5
.4
.3
.2
Increasing Power
Decreasing Power
1.0
1.2
1.4
1.6
1.8
2.0
2.2
Engine Pressure Ratio

Figure 6

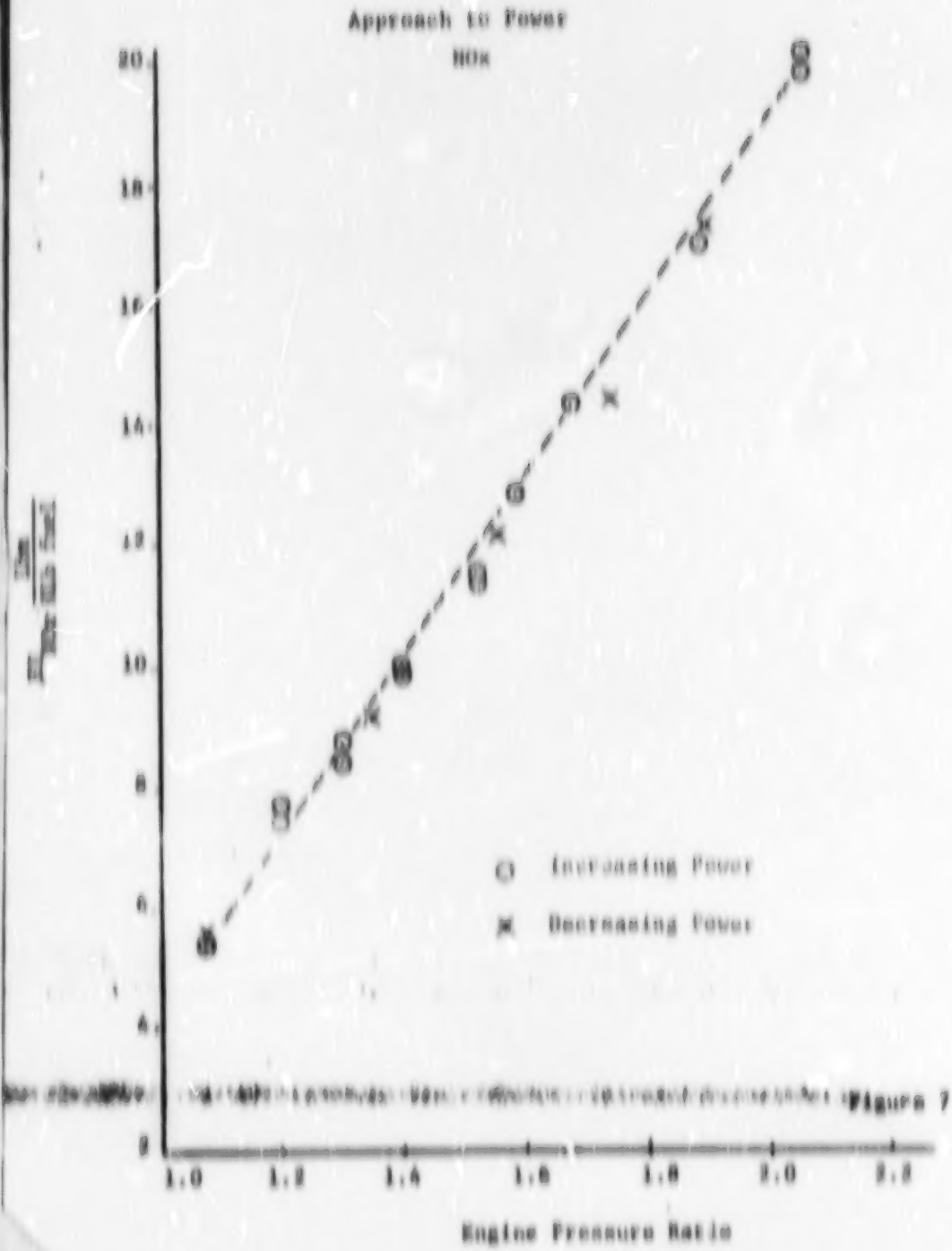
Approach to Power
NOx
20
18
16
14
12
10
8
6
4
2
0
1.0
1.2
1.4
1.6
1.8
2.0
2.2
Increasing Power
Decreasing Power
Engine Pressure Ratio

Figure 7

Sources of Uncertainty

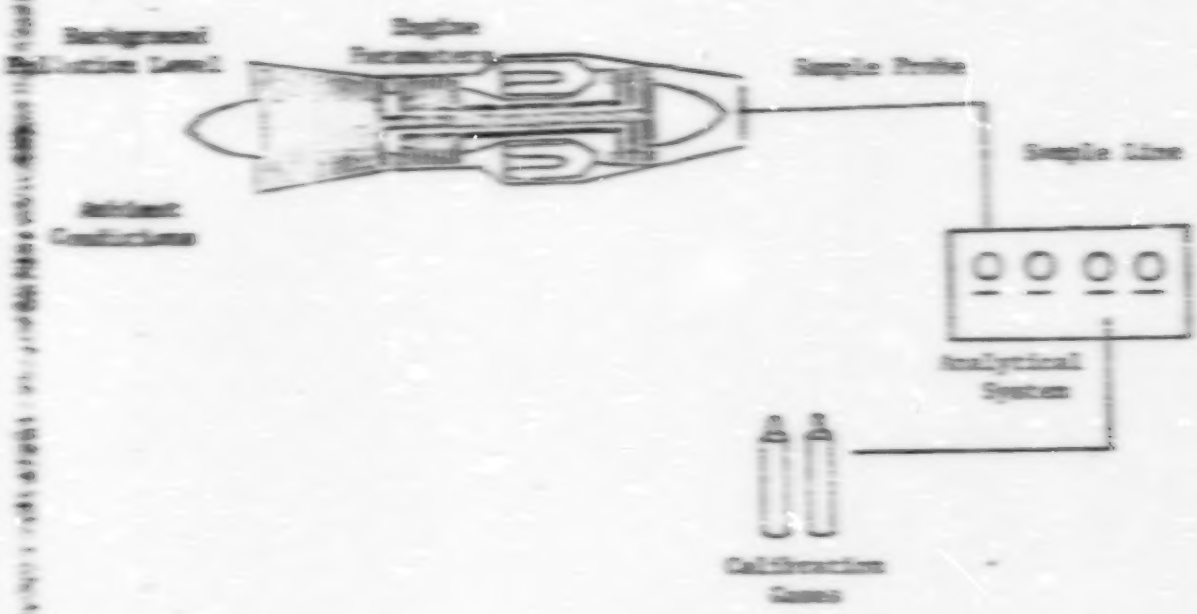

Figure 5

Low Power Carbon Monoxide

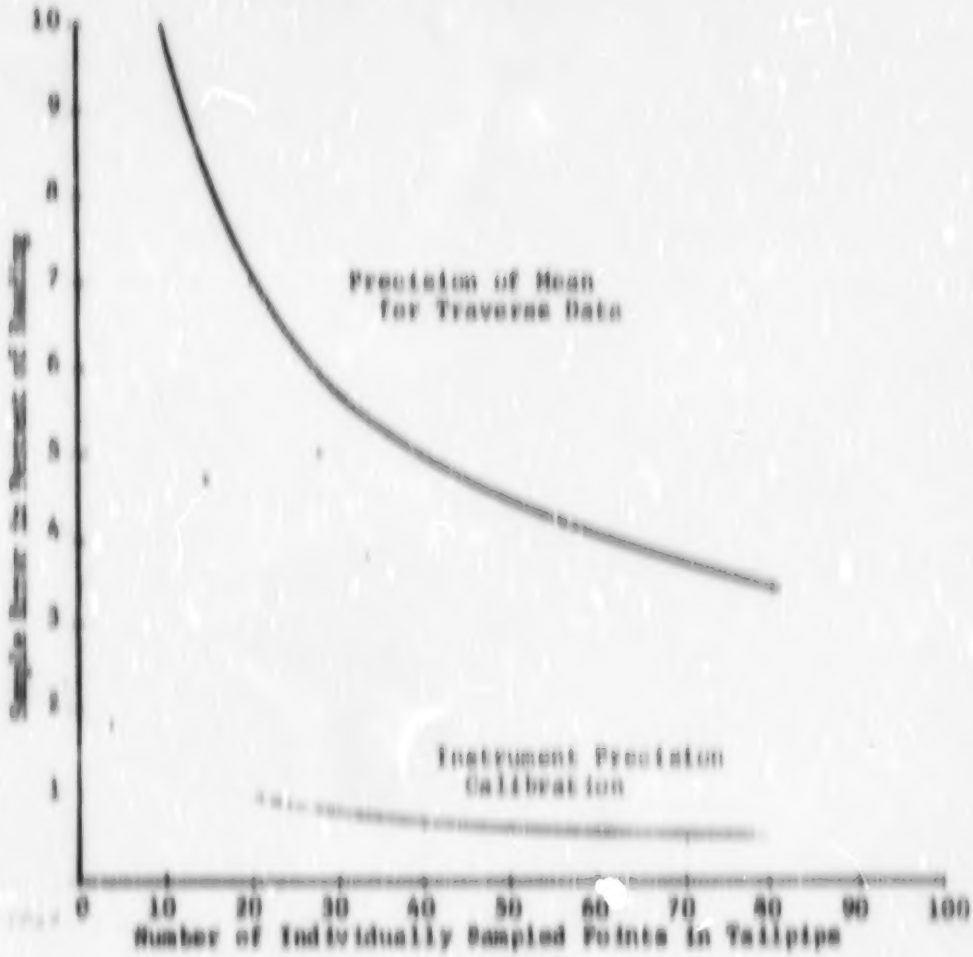

Figure 9

Reduction of sampling error with increased sampling